ARTICLES

Macrostratigraphy of North America

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ABSTRACT

The geological record is a three-dimensional mosaic of gap-bound rock bodies that, at any given scale of temporal resolution, were emplaced more or less continuously. At any geographic location, the irregular alternation of processes responsible for the formation and destruction of rock bodies results in the preservation of hiatus-bound rock packages that have a distinct time of first occurrence (base, or oldest portion), a time of last occurrence (top, or youngest portion), and a suite of defining characters (e.g., lithologies, thickness, fossils, etc.). Many important aspects of the geologic record can be quantified by compiling the stratigraphic ranges of such gap-bound rock packages. These include the quantity and spatial and temporal distribution of preserved rock, rates of rock formation, sequence stratigraphic architecture, and area-weighted rates of expansion and contraction/erosional truncation of rock emplacement settings. This approach to characterizing the rock record is scalable, permitting application to records encompassing entire continents and hundreds of millions of years as well as individual basins and geologically short time intervals. To illustrate the utility of this approach and to provide a new high-resolution analysis of the temporal structure of the geologic record, gap-bound rock packages in the continental United States and southern Alaska were compiled directly from the American Association of Petroleum Geologists Correlation of Stratigraphic Units of North America (COSUNA) charts. The COSUNA charts were assembled at a temporal resolution of approximately 1–3 million years (m.yr.) in the Phanerozoic and contain 4173 gap-bound rock packages. Many important aspects of the North American geologic record are revealed by the temporal distribution of gap-bound rock packages, including rock quantity, long-term rates of sediment accumulation, and basin turnover. The durations of gap-bound sedimentary successions are approximately exponentially distributed, with a mean duration of 25.2 m.yr. and a median duration of 16.9 m.yr. The probability of initiation and truncation among sedimentary packages does not increase or decrease substantially during the Phanerozoic, but these parameters do vary on shorter timescales in response to tectonically and glacioeustatically driven changes in sea level. The largest increase in the rate of sediment truncation occurs at the end-Permian, which marks a clear and fundamental temporal discontinuity in the sedimentary record of North America. Smaller discontinuities occur at the end-Ordovician, the end-Triassic, and the end-Cretaceous. Lithologically, Cambrian-Mississippian sedimentary successions are dominated by carbonates, and post-Paleozoic successions are dominated by terrigenous clastics. The quantity of preserved rock, the carbonate/siliciclastic ratio, and the dominant lithology comprising terrigenous clastics all vary substantially from interval to interval during the Phanerozoic, indicating that processes governing the formation and destruction of sedimentary rocks vary on timescales of <5 m.yr.

Online enhancement: table.

Introduction

Both the formation and the destruction of rock bodies occur discontinuously and selectively in time and space. The resultant geologic record is a complex spatiotemporal mosaic that neither uniformly improves toward the recent nor equally represents all settings in all intervals of time (Gregor 1968; Blatt and Jones 1975; Sloss 1976; Ronov 1978, 1994; Ronov et al. 1980; Berry and Wilkinson 1994; Veizer and Ernst 1996). At million-year timescales, the lo-

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cation and nature of sediment accumulation as well as the location and extent of sediment erosion are controlled by tectonic uplift and subsidence (Veizer and Jansen 1979, 1985), continental migration (Allison and Briggs 1993; Veizer and Ernst 1996; Walker et al. 2002), and continental freeboard (Worsley et al. 1984, 1986; Nance et al. 1986). On Milankovitch-band timescales, glacioeustatically forced sea level changes and associated climatic shifts exert a dominant control on the migration and character of depositional systems and on the locations and rates of sediment accumulation and erosion (e.g., D'Argenio et al. 2004 and references therein). In the case of igneous rocks, tectonic processes dominate both their formation and their destruction, with climatic variations influencing rates of denudation in these and other rock types (e.g., Hovius 1998; Riebe et al. 2004).

Although temporal and spatial variability in the quantity, lithology, and attributes of preserved rock is the direct result of many important geologic processes that may change dramatically on short and long timescales, there are currently few quantitative data on the distributions of rocks in time and space. Nevertheless, several important compilations that are based primarily on outcrop area measured from geologic maps have contributed greatly to our understanding of the large-scale temporal and spatial structure of the geologic record (Gregor 1968, 1985; Cook and Bally 1975; Sloss 1976; Ronov 1978, 1994; Ronov et al. 1980; Ziegler 1982), and these compilations form the basis for numerous hypotheses concerning sediment cycling and rates of continental denudation during the Phanerozoic (e.g., Hay et al. 1988; Wilkinson 2005).

Despite the empirical value of existing geologic map–based compilations of rock quantity and lithology, map-based data have two inherent limitations that diminish their utility for testing many geological hypotheses and for constraining rates of geological processes and environmental change. First, the minimum temporal resolution afforded by geologic maps on global and/or continental scales is generally on the order of epochs and periods in the Phanerozoic (i.e., several tens of millions of years) and is too coarse to address many important questions requiring million-year or finer timescales. Second, most geologic maps compiled for large geographic regions contain sparse information on many important rock properties, such as lithology and emplacement setting. This complicates meaningful comparisons of time intervals and/or regions that have similar rock quantities and/or general lithologies and makes it impossible to evaluate, for example, the potential paleobiological implications of diagenetic factors (Cherns and Wright 2000; Wright et al. 2003), taphonomic variability (Behrensmeyer et al. 2000; Kidwell and Holland 2002), and differential environmental preservation and sampling (Smith et al. 2001; Westrop and Adrain 2001; Walker et al. 2002).

In order to overcome some of these limitations and to completely summarize the temporal and spatial structure of the geologic record, five fundamental aspects of its variability must be simultaneously assessed: (1) rock quantity, (2) rock type, (3) rock geography, (4) rock emplacement setting, and (5) temporal continuity of the rock record. The first four aspects of variability in the geologic record are widely appreciated and have been addressed at a relatively coarse resolution in the Phanerozoic (e.g., Ronov et al. 1980). Temporal continuity, on the other hand, remains rather poorly understood.

Temporal continuity is defined herein as the degree to which the geologic record preserves an uninterrupted history at a given scale of temporal resolution and at a given geographic location. Temporal continuity is not the same as stratigraphic completeness (Sadler 1981; Anders et al. 1987) because geologic records with the same overall completeness may have markedly different temporal continuity.

The best summaries of the large-scale temporal continuity of the geologic record are grounded in the principles of sequence stratigraphy (Vail and Mitchum 1977; Van Wagoner et al. 1988) but are generally not quantitative. For example, Sloss (1963) identified large-scale transgressive-regressive packages of sediment in North America ("Sloss sequences"; see also Grabau 1936), and these packages serve as important organizing frameworks for tectonics and stratigraphy. Such large-scale sequences have also been used as a basis for subdividing geologic time (e.g., Golonka and Kiessling 2002). However, Sloss's and other similar descriptions of the geologic record are primarily qualitative synopses of temporal and spatial patterns in the rock record. Thus, simply recognizing that such widespread sequences exist is not generally useful for testing many geological hypotheses or for measuring the geologic processes responsible for the formation and destruction of the rock record.

At smaller spatial and temporal scales (i.e., basin scales), principles of sequence stratigraphy serve as an important organizational and interpretive framework for stratigraphic data (e.g., chronostratigraphic surfaces form fundamental subdivisions in the sedimentary record and the temporal scope of bounding unconformities determines sequence order). Sequence architecture also serves as an important framework for the predictive modeling and interpretation of unconformity and facies biases in paleobiological data (Holland 1995, 1996, 1999, 2000; Holland and Patzkowsky 1999, 2002; Scarponi and Kowalewski 2004) and in modeling and interpreting basin fill successions (Flemings and Grotzinger 1996; Syvitski and Hutton 2001). Despite the empirical utility of basic sequence stratigraphic principles, they have generally not been used to provide a high-resolution quantification of the geologic record itself. The conceptual framework for doing so is, however, firmly established and forms the basis of the approach taken here.

Gap-Bound Rock Packages as Fundamental Units

At any particular location on the surface of the earth, the entire geologic record consists of packages of rock that were deposited or emplaced continuously at a given scale of temporal resolution. These rock packages are bound by temporal gaps in the record that are recognizable at the same scale of temporal resolution. In the sedimentary record, such gaps often result from nondeposition and/or erosion and form fundamental divisions known as sequence boundaries (Vail and Mitchum 1977; Van Wagoner et al. 1988). The temporal scale of analysis (i.e., the duration threshold) defines the order of the sequence boundary and the smallest resolvable gap, but there are typically gaps in the record at many finer scales of temporal resolution, ranging all the way down to the brief moments that can separate individual bedding surfaces. The continuum of temporal continuity that is inherent in the geological record is rendered discrete only by the application of an a priori temporal resolution, and this resolution determines the scale of processes that can be detected and that are relevant in controlling the temporal and spatial structure of the rock record.

Gap-bound packages of rock are herein referred to as "packages" rather than "sequences" because packages need not correspond to traditional sequence stratigraphic boundaries and because it is preferable to reserve the term "sequence" for the entire three-dimensional gap-bound sedimentary rock body rather than for what is here treated as the fundamental unit of sampling, namely, the two-dimensional intersect that characterizes a sedimentary sequence at a particular geographic location. Moreover, packages, as used here, may include gap-bound bodies of plutonic and volcanic rock, which do not fall under the normal purview of sequence stratigraphy.

One simple but instructive analogy is to conceive of a gap-bound rock package in much the same way that a paleontologist describes the temporal span of a species. Most notably, for any time interval of interest, all gap-bound rock packages must fall into one of four categories (fig. 1), and these four categories are used to calculate temporal persistence and the number of concurrent entities at a point in time (Foote 2000)—exactly what we seek to document for the rock record. Thus, by using gap-bound packages of rock, the geologic record can be expressed in terms of analogous evolutionary parameters, including geologic diversity (the total number of packages in each time interval, or rock quantity) and geologic origination and extinction, which, in the case of sedimentary rocks, reflect spatial and temporal rates of turnover of rock bodies (i.e., the area-weighted rates of expansion, or origination, and contraction/erosional truncation, or extinction, of sedimentary environments and basins). The terms "stratigraphic extinction" and "stratigraphic origination" will be adopted here because they reflect processes that are geologically analogous to the biologic meanings of the words.

Sequences (Vail et al. 1977; Van Wagoner et al. 1988) are three-dimensional sedimentary bodies that are bound by chronostratigraphic surfaces consisting of erosional unconformities and correlative conformities. Thus, the fundamental temporal structure of a sedimentary sequence is closely re-

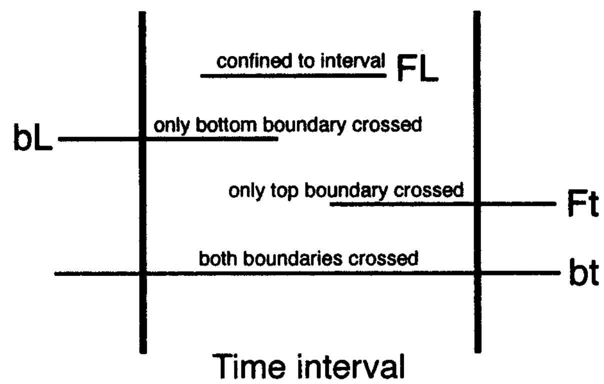

Figure 1. Four fundamental classes of gap-bound sediment packages present during a stratigraphic interval (adapted from Foote 2000). These four classes are used to calculate temporal persistence and the number of concurrent entities for paleobiological data and are here adopted for summarizing geologic data. X_{FL} = number of packages confined to an interval, X_{bL} = number of packages that cross the bottom boundary only, X_{Ft} = number of packages that cross the top boundary only, and X_{bt} = number of packages that cross both boundaries.

lated to the basic conceptual approach that is advocated here and that is used to quantify the entire North American geologic record.

To illustrate the relationship between sequence architecture and the time series of stratigraphic origination, stratigraphic extinction, and stratigraphic diversity calculated on the basis of gap-bound rock packages, a hypothetical basin-scale sequence was sampled (fig. 2). A temporal binning strategy was arbitrarily imposed on the sequence (fig. 2, *horizontal lines*), and gap-bound packages within this temporal binning framework were tabulated for an array of sampling locations along the sequence (fig. 2, *vertical lines arrayed horizontally*). The depositional sequence shown in figure 2 was adapted directly from Coe and Church (2004, their fig. 4.11) and illustrates an idealized geometry for a sequence deposited along a passive ramp margin.

Temporal patterns in the time series of stratigraphic extinction, stratigraphic origination, and stratigraphic diversity (fig. 2, *left*) reflect the magnitudes of the sequence stratigraphic boundaries and general geometry and spatiotemporal structure of the sequence highlighted in this example. The abrupt unconformity in figure 2 (time interval t_6) is clearly demarcated by a large pulse of stratigraphic extinction with no corresponding pulse in stratigraphic origination and is followed by a substantial decline in stratigraphic diversity. This peak in stratigraphic extinction occurs because many gap-bound packages of rock terminate in the sequence boundary and because few packages span that interval. Sediments deposited after the abrupt unconformity are characterized by low package diversity and relatively high rates of package turnover (i.e., rates of stratigraphic extinction and origination are both high). This occurs because the area of deposition contracts and shifts rapidly basinward. When the basinward shift in deposition stops and the preserved sedimentary record begins to expand spatially, stratigraphic extinction drops to zero. Stratigraphic origination rate also declines because of an expansion-induced increase in the number of through-ranging rock packages. The number of packages (stratigraphic diversity) also begins to increase steadily at this time as preserved sediment expands spatially to cover more area. Finally, during transgression and landward shift in deposition, both stratigraphic extinction and origination increase substantially as deposition shifts laterally and simultaneously expands (i.e., high spatial turnover of sediment accumulation combined with overall expansion of sediment area). The expansion of sediment accumulation at the flooding interval also results in the largest area of preserved sediment in the sequence and therefore a maximum in the number of packages.

The hypothetical sequence in figure 2 demonstrates that many familiar sequence stratigraphic patterns can be quantitatively identified and summarized by tabulating gap-bound packages of rock. However, this approach is sensitive to the spatial distribution of sampled columns. If, for example, sampling were preferentially concentrated in one geographic region, such as the region that is represented almost entirely by low-stand sediments, then this portion of the sequence would contribute disproportionately to the computed stratigraphic time series (fig. 2, *left*). It is therefore important to choose column locations in a way that is random with respect to the underlying architecture of the targeted geologic record or to array them uniformly, as shown in figure 2. Alternatively, if the goal is to achieve an area-independent weighting of the sequence shown in figure 2, then equal numbers of columns could be selected or subsampled from each portion of the sequence and the relevant time series computed from these.

Although compiling the ranges of gap-bound packages of rock affords a rather complete quantitative summary of the temporal and spatial structure of the preserved geologic record, the first and last occurrences (i.e., bases and tops) of gap-bound rock packages need not correspond to the true times of initiation and cessation of rock emplacement processes. For example, major sequence boundaries will typically be associated with subaerial exposure and erosion of previously deposited sediment. In most cases, determining the temporal and spatial extent of the sediment that was removed by erosion will be difficult, if not impossible, and therefore the time of last occurrence of a sediment package will generally represent an erosional truncation of unknown magnitude. The bases of rock packages, on the other hand, record the actual onset of sedimentation and are therefore not artificially truncated by extensive removal of previously deposited sediment (although the bases of gap-bound packages may be very condensed by slow rates of sedimentation). Asymmetry in the processes that result in the preserved ranges of packages may have important implications for the interpretation of stratigraphic time series, but such issues do not affect the value of the metrics as a complete description of the temporal and spatial structure of the preserved geologic record.

All preserved sediment was treated identically in the example sequence (fig. 2), but it is possible to perform the same analysis for a lithologically or

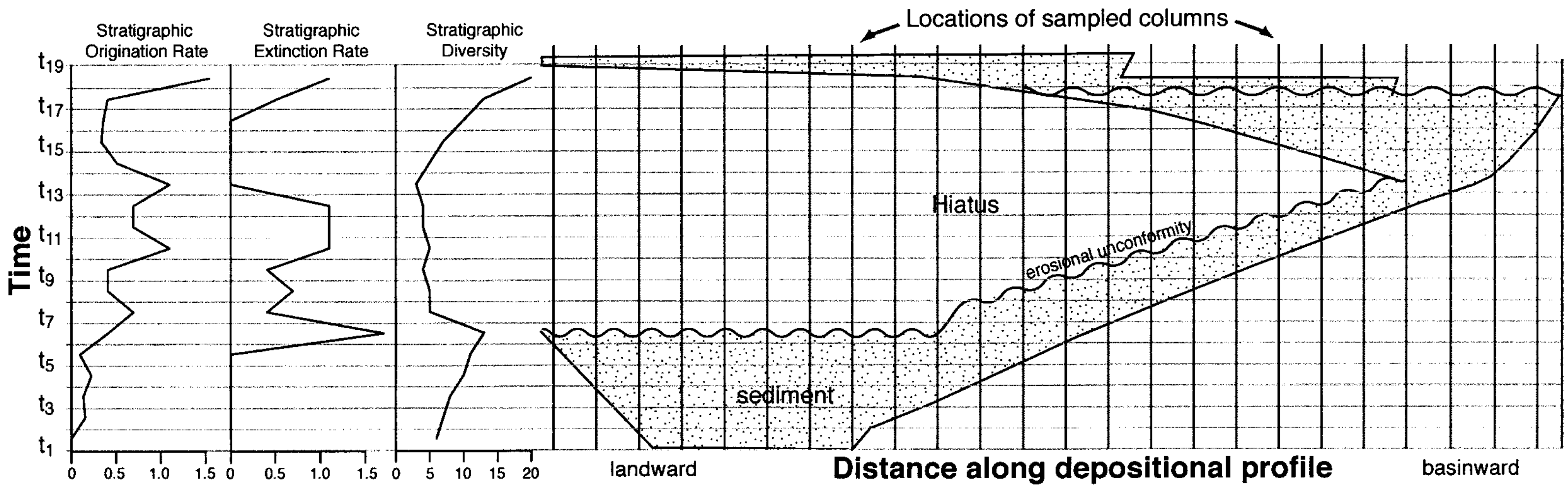

Figure 2. Hypothetical sequence geometry (adapted from Coe and Church 2004) for a passive ramp margin in time (*vertical*) and space (*horizontal*) and its relationship to corresponding time series of stratigraphic turnover and diversity. *Stippled area* = preserved sediment; *open area* = hiatus. Temporal binning strategy is represented by the through-going horizontal lines. The four types of gap-bound packages (fig. 1) were counted at each vertical sampling transect and then aggregated to compute the time series of stratigraphic turnover and diversity for the basin. Rates of stratigraphic turnover are survivorship-based rate metrics (Foote 2000): extinction = $-\ln[X_{bt}/(X_{bt}+X_{bL})]$, origination = $-\ln[X_{bt}/(X_{bt}+X_{Ft})]$. This simple example illustrates the relationship of stratigraphic diversity and turnover parameters to sequence architecture within the familiar scale of a single depositional basin, but the general approach can be scaled up to quantify the macrostratigraphic architecture on a continental scale (or down to include finer-scale temporal and spatial phenomena).

environmentally defined subset of the rock body. For example, if the sequence shown in figure 2 preserved both marine and terrestrial sediments, then the analyses could be repeated for only the marine component. Gaps would, in this case, include both erosional hiatuses that truncate marine sediment and terrestrial interruptions in the marine sedimentary record.

The example illustrated in figure 2 pertains to a portion of a single sequence within a single depositional basin, but the general approach can be extended to include multiple sequences and multiple depositional basins spanning entire continents. The resultant time series of geologic turnover and geologic diversity would, in this case, reflect the average temporal and spatial dynamics of the large-scale aggregate geologic record (i.e., macrostratigraphic architecture). Rapidly evolving tectonic basins and slowly subsiding interior cratonic basins would, in this case, be treated equivalently and would contribute to the overall temporal pattern in proportion to the number of packages representing each basin type. If sampling is randomly distributed or regularly arrayed in space, then the contribution of different basins will be weighted according to their area. In the analyses that follow, this is the relevant interpretive framework.

Methods: Correlation Charts as a Source of Data

Because gap-bound packages of rock constitute a fundamental temporal architecture that emerges as a result of discontinuous processes of rock formation and destruction, compilations of these data are widely available in the form of correlation charts. However, such data have rarely been compiled and used in a systematic fashion or analyzed quantitatively.

To demonstrate the efficacy of the package-based approach outlined above, the American Association of Petroleum Geologists Correlation of Stratigraphic Units of North America (COSUNA) charts (Childs 1985) were used to rapidly compile the temporal ranges, thicknesses, and general lithologies of gap-bound rock packages in the continental United States and southern Alaska. All data were manually read from the physical charts and entered into a customized relational database for analysis. Human-induced data-entry errors occurred at two critical steps (reading the charts and entering the data), but limited cross-checking suggests that error frequencies are relatively low (less than one error per COSUNA column) and random (errors do not appear to be concentrated in specific time intervals) and are therefore unlikely to have substantially biased the major features of the results presented here.

The COSUNA correlation charts provide a rather complete description of the known geologic record that is resolved at a minimum temporal resolution of substages and stages in the Phanerozoic (Salvador 1985). Both surface and subsurface geologic data are included on all of the COSUNA charts, but it is usually impossible to determine from the physical charts alone which portions of a stratigraphic column are known only from the subsurface. The minimum duration required for the explicit identification of a gap on the COSUNA charts is also not explicitly stated, but gaps encompassing a small fraction of one stage are commonly represented. The inferred temporal resolution based on the chart data is approximately 1–3 million years (m.yr.), but actual temporal resolution undoubtedly varies regionally according to the state of knowledge at the time of chart publication (generally the early and mid-1980s). Although the COSUNA charts were compiled prior to the widespread application of outcrop-based sequence stratigraphy, the COSUNA charts resolve most second-order sequences. Many third-order sequence boundaries are, however, not resolved because they generally fall below the temporal threshold required for gap recognition.

It should be noted that the COSUNA data were compiled by field geologists who are intimately familiar with the regions covered by each of the 20 correlation charts. Thus, these data are surprisingly little removed from field observations, given the scope of the compilation. Nevertheless, knowledge of the geologic record necessarily varies regionally and temporally, and therefore some aspects of the results presented here may reflect our understanding of the record rather than its intrinsic properties. However, it is unlikely that such uncertainties have conspired in reinforcing ways so as to overwhelmingly dominate the temporal patterns on a continental scale.

Although the temporal resolution of the COSUNA charts is quite acute for Phanerozoic-scale analyses, the results presented here are summarized by binning gap-bound packages into what are mostly stages in the Paleozoic and Mesozoic and subepochs in the Cenozoic (see table A1 available in the online edition or from the *Journal of Geology* office). Thus, individual columns can have multiple packages within a single stage because the temporal resolution of the COSUNA charts is finer than the stratigraphic bins used in these analyses. Because of limitations in the temporal resolution afforded by the COSUNA charts, the Lower and Middle Cambrian were not subdivided for the present analyses. Dates for interval boundaries were based on those of Gradstein et al. (2004) for most of the Phanerozoic. In the Cambrian and Ordovician, which are not fully resolved by Gradstein et al. (2004), dates for intervals between major epoch and period boundaries were interpolated (table A1).

Figure 3 shows a detailed mock-up of two columns on one of the COSUNA charts. There is one gap-bound package of rock in column 1 and two gap-bound packages of rock in column 2. The first and last occurrences (stratigraphic ranges) of each of these gap-bound packages can be read from the left-hand side of the chart, which illustrates the temporal resolution employed for much of the Paleozoic. Note that, in addition to providing rock age, the charts also provide lithologic data (imperfectly reproduced by different shades in fig. 3), as well as group, formation, and/or member names, thickness, and general contact relations between adjacent stratigraphic units. It is therefore possible to calculate parameters such as average rock accumulation rates and to conduct analyses for individual lithologies or subsets of lithologies. For example, instead of including all rock types in each package (as shown in fig. 3), the ranges of gap-bound carbonate packages can be derived. In this case, column 1 would contain one gap-bound carbonate package, and column 2 would contain four.

This example (fig. 3) is rather straightforward, but much more complex columns occur on the COSUNA charts because individual columns rarely record the unambiguous and easily defined one-dimensional geologic record that would be obtained by drilling a hole at a particular point on the surface of the earth and then recording all rock units and their ages from the surface to the base of the hole. Instead, the COSUNA columns are predominately composite stratigraphic columns that attempt to summarize the lateral variability of the geology over a targeted region. For example, several columns on the COSUNA charts are clearly divided into two or rarely three subcolumns that reflect the lateral variability characterizing the rock record of the region represented by the column. In such cases, gap-bound packages were compiled separately for each subcolumn. In cases where individual units on the COSUNA charts are split into lateral equivalents but are not consistently and clearly delimited into separate subcolumns (e.g., fig. 3, *top package*, *column 2*), the units were not treated as

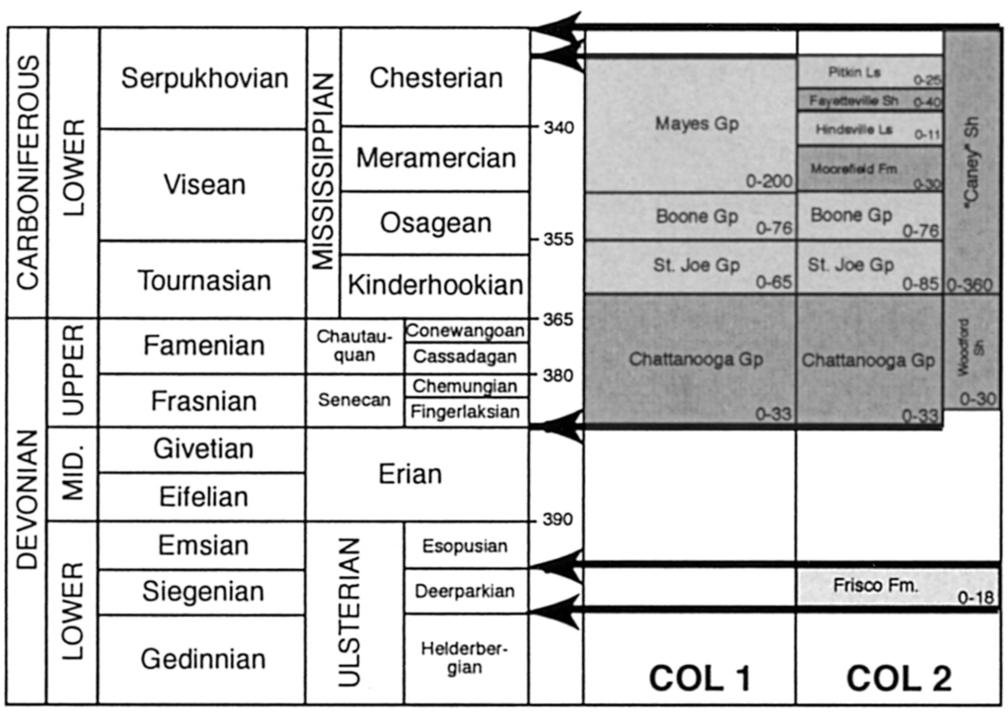

Figure 3. Example portion of two columns on one of the COSUNA charts. Horizontal arrows designate first and last occurrences for gap-bound rock packages for both columns. White area in each column represents hiatuses. Shades of gray within rock packages reflect different lithologies. In this case, the lighter units are carbonates, and the darker units are clastics. See text for further explanation regarding how data were compiled from the charts.

separate subcolumns but were instead subsumed into a single gap-bound rock package. Analyses conducted for separate lithologies did, however, include all appropriate subunits, including lateral equivalents (e.g., fig. 3, *top package*, *column 2*, still contributes three different carbonate packages bound by shale gaps even though all three carbonate packages are laterally equivalent with shale in this column).

The COSUNA charts occasionally record contiguous packages of rock that are interrupted by a complete change in major rock type (e.g., sedimentary overlain by volcanic overlain by sedimentary within one contiguous rock package). In these cases, the package was broken into two or more separate packages at the major rock type boundaries. Instances of such nonconformities are relatively few on the COSUNA charts, but it is relatively common, for example, for volcanic rocks to have no resolvable temporal gap with underlying or overlying sediments in a single temporally continuous rock package. In such cases, two packages were identified—one comprising the sedimentary component and one comprising the volcanic component. A similar procedure was followed when compiling the gap-bound packages for separate sedimentary lithologies within a single sedimentary COSUNA package.

Although the COSUNA charts represent composite stratigraphic columns, the density of sampling in the United States is rather high, and therefore the region represented by each column is comparatively small (fig. 4). All told, 541 columns from the continental United States and southern Alaska were compiled from the COSUNA charts (fig. 4). The distribution of column locations shown in figure 4 was not randomly generated but instead reflects the conscious efforts of the data compilers to adequately capture the complexity of the geologic record (Childs 1985). Structurally complex regions, such as those that characterize the continental margins, have a higher density of columns because the spatial heterogeneity of the geologic record necessitates such sampling. This is particularly true in regions that have experienced net crustal shortening and where palinspastic reconstruction would result in more widely spaced sampling intervals in these regions. Nevertheless, because the macrostratigraphic statistics calculated here are sensitive to the distribution of sampled locations (fig. 2), results are inevitably influenced by the spatial density of sampling shown in figure 4. However, it is unlikely that the spatial distribution of COSUNA sampling locations has strongly biased the continental-scale patterns documented here.

Figure 4. Map showing location of all 541 columns compiled from the COSUNA charts.

From the first- and last-occurrence data, time series of diversity (total packages), as well as stratigraphic extinction, origination, and sedimentation rates, were calculated for the aggregate data and for individual lithological subsets. The ranges of carbonate and siliciclastic components of mixed carbonate-siliciclastic packages (i.e., fig. 3, *column 2*) were determined by assembling the temporal ranges of individual lithologies within mixed packages and then determining gap-bound packages on the basis of those individual ranges.

Packages in each time interval were assigned to one of the four characteristic types illustrated in figure 1, and survivorship-based rate metrics were calculated using the equations of Foote (2000). These metrics are based on the probability of persistence from one interval boundary to the other, which, in the case of a Poisson process, is given by e^{-rt}, where r is the per-package rate in question. The ratio of packages that span an interval to those that cross only one of the interval boundaries is therefore equal to this exponential. Solving the equation for r yields the rates of either forward (bottom boundary, extinction) or backward (top boundary, origination) temporal persistence that are used here (Foote 2000). In the case of geologic data, such rates of temporal persistence reflect the life spans and temporal rates of turnover of rock emplacement settings as well as the area-weighted rates of expansion and contraction of preserved rock bodies.

Results

A total of 4173 gap-bound rock packages were compiled from the COSUNA charts; 3221 of these packages are sedimentary, 688 are intrusive or extrusive igneous rocks, and 264 are metamorphic. Of the sedimentary packages, 371 have been designated as nonmarine in origin. The remaining 2847 sedimentary packages were treated as marine, although some unknown proportion of these includes nonmarine sediments.

Sedimentary Rocks: Quantity and Lithofacies. Figure 5 summarizes the total number of preserved sedimentary rock packages in the continental United States and southern Alaska for 74 Phanerozoic time intervals (median duration = 5.6 m.yr.). Because the total number of packages preserved in each interval is an approximate measure of the area of preserved sediment, it is possible to crudely estimate preserved sediment volume, given only the average area per COSUNA column (1.64×10^4 km^2) and the average thickness of each sedimentary rock package (0.84 km). This gives an estimated preserved sediment volume in the Lower Cambrian of 1.35×10^6 km^3. Assuming that the Lower Cambrian record of the United States is representative of the global continental sedimentary record, then the global volume of preserved Lower Cambrian sediment (excluding Antarctica) is here estimated to be 20.6×10^6 km^3. Despite the crude nature of this calculation, this estimate is within 21% of Ronov et al.'s (1980) estimate of 26.0×10^6 km^3 for the global volume (excluding Antarctica) of preserved Lower Cambrian sediment.

The time series of total sedimentary packages shows several important patterns (fig. 5). First, rock quantity increases from the Lower Cambrian to the Upper Cambrian, decreases sharply in the Middle Ordovician, and then increases to a Paleozoic high in the Caradocian. After the Upper Ordovician, the total number of sedimentary packages slowly declines to another local minimum in the Lower Devonian, increases to a local high in the Late Devonian, and then irregularly declines to an all-time low at the Permo-Triassic boundary. The Permo-Triassic rock quantity minimum (Newell 1952; Raup 1972; Peters 2005) is the most widely appreciated aspect of the fundamental discontinuity that divides the Paleozoic and post-Paleozoic sedimentary rock records of North America. After the Permo-Triassic minimum, the number of preserved sedimentary packages increases through the Mesozoic, declining modestly after achieving a Mesozoic high during the Cenomanian. An abrupt increase to an all-time maximum occurs during the late Neogene because of the prevalence of nonmarine sediment in young time intervals.

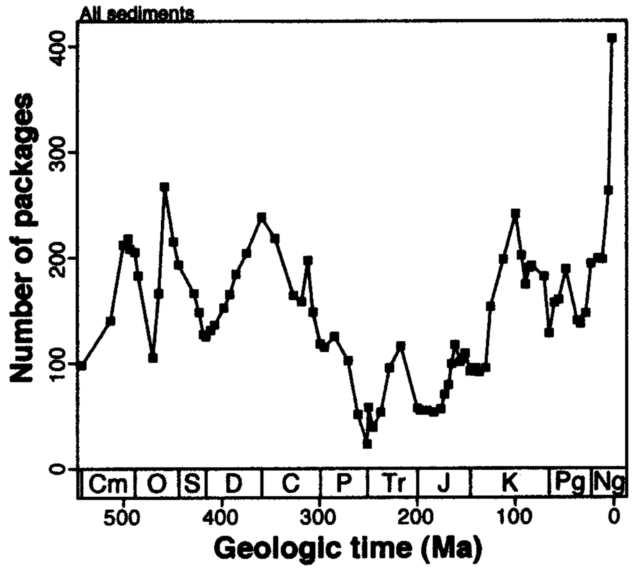

Figure 5. Time series of the total number of sedimentary packages, irrespective of lithology or depositional environment. The total number of packages in each time interval is an area-weighted measure of rock quantity, and this measure achieves a Phanerozoic minimum at the Permo-Triassic boundary. Data are plotted at age for each interval base.

The absolute and relative abundance of the lithofacies that comprise sedimentary rock packages changes substantially on both short and long timescales during the Phanerozoic (fig. 6). The total number of sedimentary packages shown in figure 6 is exaggerated relative to figure 5 in time intervals that are lithologically heterogeneous because contiguous sedimentary packages were broken into two or more packages at the lithofacies breaks identified in figure 6. Temporal patterns should therefore be emphasized over absolute values.

The most fundamental aspect of lithofacies composition in the Phanerozoic sedimentary record of North America is a compositional shift from carbonate dominated in the Paleozoic to almost exclusively terrigenous clastics in the Cenozoic. In absolute terms, carbonate abundance increases abruptly in the Early Cambrian and then remains volatile while declining slightly for the remainder of the Paleozoic. The peak in carbonate dominance that occurs during the pinnacle of the "Great American Carbonate Bank" (Ginsburg 1982) in the Late Cambrian and Early Ordovician is relatively short lived but unrivaled in the Phanerozoic of North America. More than 80% of the sedimentary rock

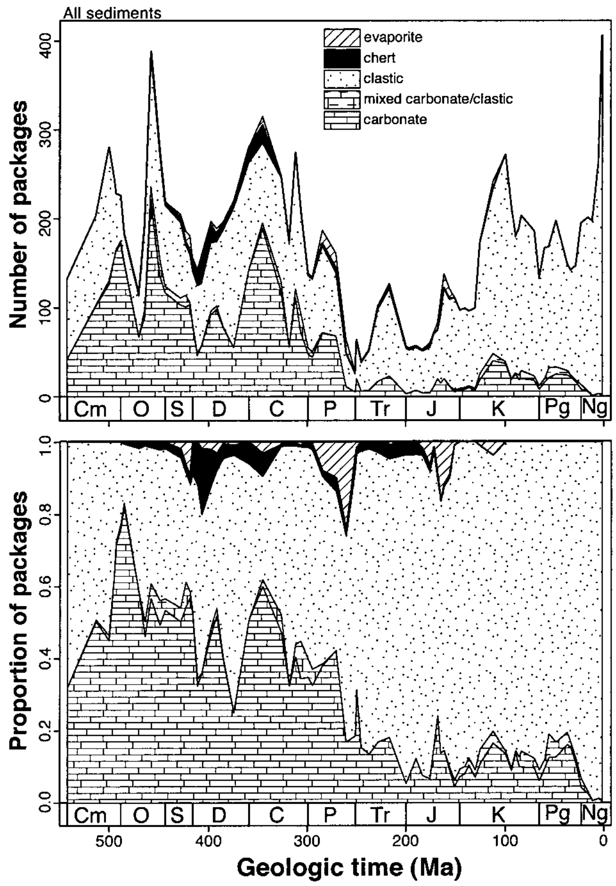

Figure 6. Time series of absolute (*top*) and relative (*bottom*) abundance of sedimentary lithofacies measured as the total number of packages preserved in each time interval. Mixed carbonate/clastic refers to rock units that are explicitly stated to be mixed on the COSUNA charts. Figure shows the Phanerozic shift from a carbonate-dominated sedimentary record to a clastic-dominated record as well as short-term variability in sedimentary rock composition. Data are plotted at age for each interval base. See text for explanation of the effects of subdividing packages by lithology.

packages in the Late Cambrian and Early Ordovician are carbonates (fig. 6). This peak in carbonate abundance is followed by an Ordovician through Early Carboniferous carbonate plateau that is interrupted by two large declines: one in the Late Silurian–Early Devonian and one in the Late Devonian. The Late Devonian drop in carbonate abundance is accentuated in a relative sense by the simultaneous expansion of siliciclastic sediments during this time. A local maximum in carbonate abundance immediately follows the Devonian, and this corresponds to the widely recognized Mississippian expansion of carbonate shoals and ramps over siliciclastic-dominated basins in North America (Ausich 1997).

In the latest Permian, carbonate abundance declines to a Paleozoic minimum and then persists at low levels for the rest of the Phanerozoic. The long-term replacement of carbonates by siliciclastics appears more gradual and continuous when lithofacies abundance is expressed proportionally (fig. 6, *bottom*). A long-term decline in global carbonate abundance has been recognized by many workers (Ronov 1978; Ronov et al. 1980; Walker et al. 2002), and the Phanerozoic migration of Laurentia from low to mid-latitudes (Hay et al. 1983; Allison and Briggs 1993; Veizer and Ernst 1996) is at least partly responsible for the overall decline in carbonates documented here.

In addition to important short-term variability in the carbonate-siliciclastic records, cherts and evaporites also highlight important compositional trends and breaks in the Phanerozoic sedimentary record of North America. Most notably, no substantial deposits of evaporites occur in North America until the Silurian. This delay may reflect the lower Paleozoic buildup of expansive carbonate platforms that restrict circulation over large areas of epicontinental seaways, thereby accentuating environmental impacts of modest changes in sea level. A prominent pulse in evaporites during the Permian records the last remnants of the great Paleozoic epicontinental seas. Similarly restricted epicontinental, marginal marine settings also occur in the Jurassic of North America and are clearly identified by a pulse of evaporites in the COSUNA data. Evaporites almost completely disappear from the stratigraphic record of North America after the Cretaceous. This may be related to the shift of North America from low to mid-latitudes, as discussed above, but it may also be driven by the disappearance of epicontinental seas in restricted cratonic basins that favor extensive evaporite formation (Railsback 1992).

Figure 6 combines all terrigenous siliciclastic sediments into a single lithofacies category, but there is also important temporal variation in the types of lithologies that dominate siliciclastic sediments. Figure 7 shows patterns of absolute and relative abundance of some of the major siliciclastic sediment types. As in figure 6, siliciclastic packages were broken into multiple packages at the boundaries between the major lithofacies. Thus, a single siliciclastic package used in the tabulation for figure 6 may be represented by two or more siliciclastic packages in the tabulation for figure 7 if there are prominent compositional shifts in siliciclastic lithofacies within that package. Sedi-

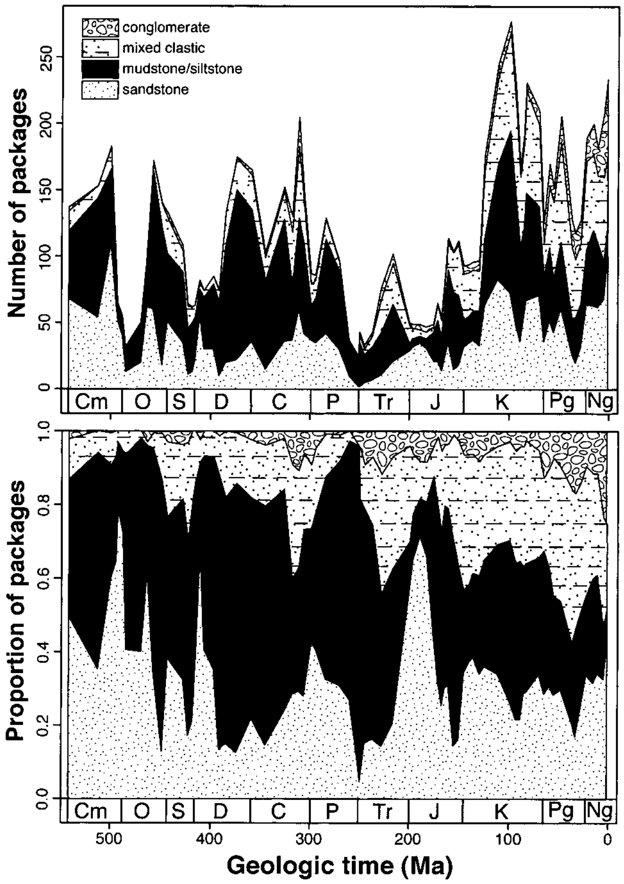

Figure 7. Time series of absolute (*top*) and relative (*bottom*) abundance of terrigenous clastic lithofacies measured as the total number of packages in each time interval. Data are the same as for the clastic component in figure 6, but here clastic packages have been subdivided on the basis of the listed lithologies; packages I designated as "terrestrial and volcaniclastic" (dominated by Cenozoic alluvium and drift) were excluded. Figure shows the prominent short-term variation in the fine- and coarse-grained components of the terrigenous clastic record. Note the Cenozoic increase in the number of conglomerate packages. Data are plotted at age for each interval base.

ments that were designated in my data compilation as "terrestrial and volcaniclastic" (packages that are dominated by alluvium and glacial drift or that contain conglomerates and volcanigenic sediments) were not included in figure 7 because this category is not particularly lithologically informative and because it increases dramatically during the Cenozoic, obscuring some siliciclastic lithofacies patterns.

The most striking aspect of the relative abundance of siliciclastic sediments is the marked short-term variability in intervals that are dominated by fine- and coarse-grained siliciclastic sediments. Pulses of coarse-grained sediment, such as those that occur in the late Cambrian, Early Devonian, and Late Triassic–Early Jurassic, generally correspond to extensive regressions (Hallam 1984; Hallam and Wignall 1999) and the spread of coarse siliciclastic sediment over depositional basins. The exception to this is the dominance of fine-grained sediment in the Early Triassic, which may reflect the prevalence of relatively low-gradient, shallow tidal and alluvial environments in this interval in western North America (e.g., Moenkopi Formation). Increases in the abundance of coarse-grained sediment also reflect the progradation of siliciclastic wedges from orogenic fronts. The most prominent example of this may be the steady increase in the proportion of coarse-grained sediment that occurs during the later part of the Carboniferous as the Appalachian Basin fills and as sedimentary wedges prograde westward at the height of the Alleghenian orogeny (e.g., Rast 1984; Bennington 2002). On longer timescales, the average siliciclastic record of North America coarsens upward such that mud and silts are more prevalent in Paleozoic packages than they are in Mesozoic and Cenozoic packages.

Sedimentary Rocks: Terrestrial Record. The most striking aspect of the terrestrial sedimentary record is that it is strongly temporally asymmetric. The number of preserved terrestrial packages increases by more than one order of magnitude during the Late Cretaceous and Cenozoic (fig. 8). There is no similar dramatic increase in the number of packages in the marine sedimentary record (fig. 1 in Peters 2005).

The large increase in the number of terrestrial packages begins to accelerate in the early Cenozoic and continues to accelerate for most of the interval. This stands in stark contrast to the pre-Cenozoic history of the terrestrial record, which exhibits virtually no temporal trend (fig. 8). Because nonmarine sediments are not always explicitly identified as such on the COSUNA charts, enhancing the environmental resolution of the COSUNA data stands to significantly increase the number of Mesozoic and late Paleozoic terrestrial packages. However, it is unlikely that imperfect disentanglement of the marine and terrestrial sedimentary records will completely remove the Cenozoic increase documented here because the whole Phanerozoic was subject to the same environmental uncertainty. Moreover, Ronov et al. (1980) also reported a substantial increase in the amount of terrestrial clastic sediment during the Cenozoic.

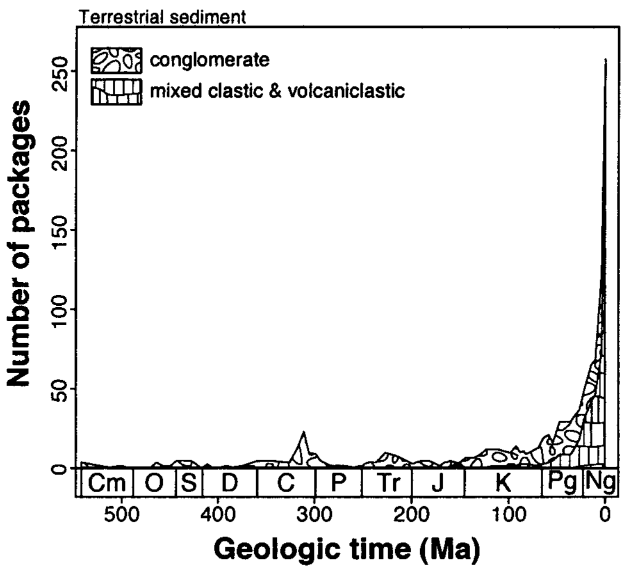

Figure 8. Time series of the total number of packages explicitly designated as nonmarine in origin on the COSUNA charts. The total number of packages is subdivided into conglomerate and mixed clastic and volcaniclastic facies. The latter category is dominated by alluvium and drift and includes many conglomerates and breccias. The total amount of preserved terrestrial sediment increases by more than one order of magnitude late in the Phanerozoic. Compare to all sedimentary rocks in figure 5, most of which are marine in origin. Data are plotted at age for each interval base.

Sedimentary Rocks: Temporal Continuity. Time series for each of the four characteristic types of sedimentary packages (Foote 2000) in each Phanerozoic time interval are shown in figure 9. There is considerable short-term variability in each of the four characteristic package types, but there are no significant long-term temporal increases or decreases (though there are important temporal patterns). The large Pleistocene increase in the number of X_{FL} and X_{bL} packages and the corresponding decrease in X_{Ft} and X_{bt} packages reflects, in part, an edge effect because the Pleistocene was the last time interval used in this analysis. There is no similar edge effect at the start of the Cambrian because the Precambrian record was included in the data compilation.

For most of the Phanerozoic, the majority of packages in each time interval span that interval (X_{bt}), but there are several intervals in which more packages terminate or originate. These intervals form important breaks in the temporal continuity of the sedimentary record that will be more apparent when rates of stratigraphic turnover are examined. The sharp drop in the absolute number of packages that span the Paleozoic-Mesozoic boundary (Permian-Triassic trough in X_{bt}) reflects the major discontinuity in sedimentation that occurs across this boundary.

The pronounced break in the temporal continuity of sediment accumulation that distinguishes the Paleozoic and post-Paleozoic sedimentary records of North America is perhaps most clearly revealed when the durations of gap-bound sedimentary packages are plotted at their times of first or last occurrence (fig. 10). The gray triangles in figure 10 show the regions occupied by packages that are contained entirely within the Paleozoic or entirely within the post-Paleozoic. The intervening unshaded region circumscribes the space that would be occupied by sedimentary packages spanning the Permo-Triassic boundary. The lack of points in the open area and the density of points in the shaded areas indicate that the sedimentary record of North America can be characterized by two temporally disjunctive bodies of sediment: one that accumulated in the Paleozoic and one that accumulated in the post-Paleozoic. Within the Paleozoic and post-Paleozoic intervals, there are also discontinuities in the temporal continuity of the sediment record, but these discontinuities are much smaller than the fundamental break that defines the end-Paleozoic sedimentary record of North America.

The probability that sedimentary packages persist from one interval to the next can be measured using the survivorship-based rate metrics of Foote (2000). Note that these per-interval rate estimates correspond to exponential rate constants and can therefore be greater than unity. Figure 11 shows the time series of rates of stratigraphic extinction and stratigraphic origination calculated on a per-interval basis for all sedimentary packages. The Late Permian is clearly identified as the largest per-interval pulse of stratigraphic extinction in the Phanerozoic, but stratigraphic extinction rate increases throughout the entire Permian, not just in the last stage of the Permian.

To evaluate the significance of the observed extinction rate peaks, the observed sedimentary packages were randomly sampled, with replacement, and then placed, in continuous time, randomly into the temporal binning framework used here. The resultant time series of stratigraphic extinction and origination for the randomized packages were then calculated and the maximum rate estimate recorded for each iteration. The dashed lines in figure 11 show the frequency with which the randomized packages exhibited at least one rate estimate in any

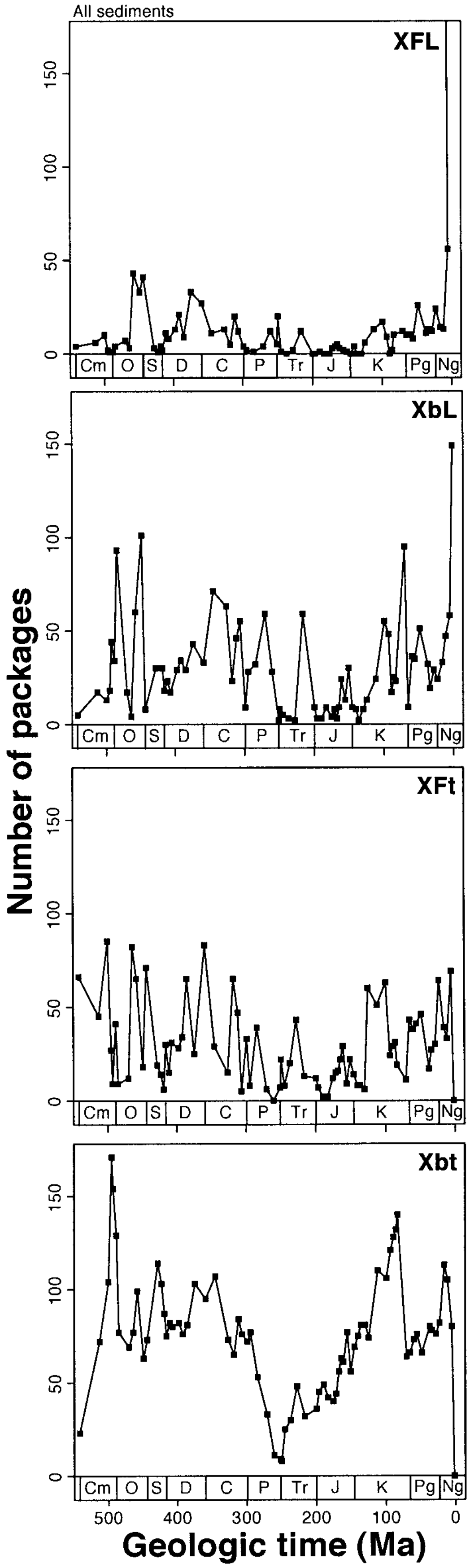

Figure 9. Time series for each of the four fundamental types of packages in each stratigraphic interval (see fig. 1). Note the Phanerozoic low in the number of through-ranging packages (X_{bt}) at the Permian/Triassic boundary interval. The large Pleistocene increases in the number of X_{Ft} and X_{bL} packages reflect an edge effect because the Pleistocene was the last time interval included in this analysis and therefore all packages must fall into one of these two categories. There is no similar Lower Cambrian edge effect. Data are plotted on identical ordinates at the ages for each interval base.

time interval as large as or larger than the value of the horizontal line.

The peak of stratigraphic extinction observed at the end-Permian is greater than all of the extinction peaks obtained in 1000 randomization iterations and is therefore far outside the range of values expected on the basis of chance alone. The observed Guadalupian and end-Triassic stratigraphic extinction peaks are also large in comparison to what is expected on the basis of randomly distributed sedimentary packages. Fewer than 10% of the randomizations yielded one or more extinction rates as great as or greater than the magnitude of extinction observed at the end-Ordovician and end-Cretaceous. Thus, there are several stages in which the rate of sedimentary package truncation is concentrated, and these intervals form important discontinuities in the sedimentary record of North America that are not easily explained by a homogeneous model of constant truncation probability.

Significant pulses of stratigraphic origination also occur at the beginning of the Paleozoic and Mesozoic eras. The large "Cambrian explosion" of sedimentary package origination is not an edge effect because packages from the Precambrian were also compiled. Instead, the Lower Cambrian pulse of stratigraphic origination corresponds to the onset of the first major marine transgression preserved extensively on Precambrian basement in Laurentia: the "great unconformity" at the base of the transgressive Sauk sequence (Sloss 1963), which culminated in the Great American Carbonate Bank discussed above. The pulse of origination that occurs at the base of the Mesozoic is primarily the result of a more modest, but proportionally no less important, expansion in the area of preserved sediment during the Early Triassic.

It is important to note that there is significant and considerable interval-to-interval variability in the rate of stratigraphic extinction and stratigraphic origination during the Phanerozoic, but there is no

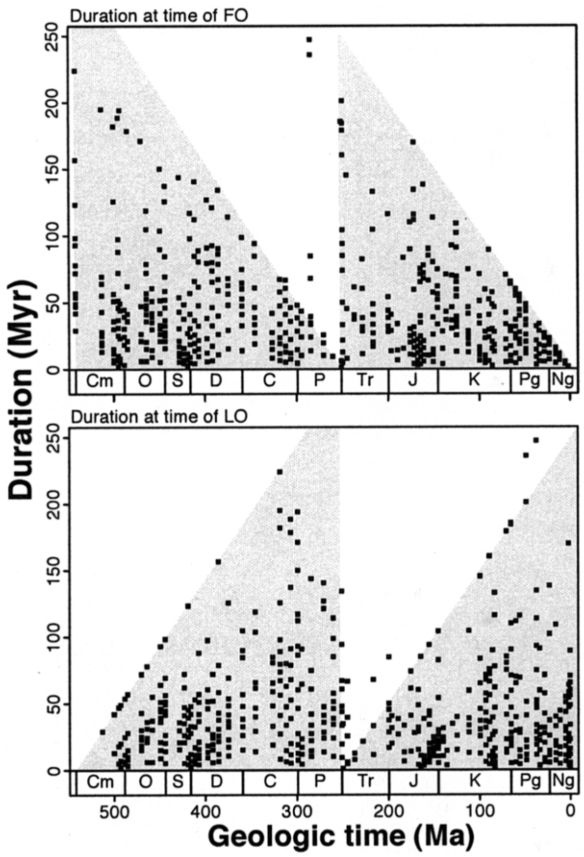

Figure 10. Duration of all sedimentary rock packages plotted at their time of first occurrence (FO, *top*) and last occurrence (LO, *bottom*). Abscissa values correspond to the age of the base of the relevant time interval. Shaded triangles designate areas occupied by packages that fall completely with the Paleozoic (*left*) or post-Paleozoic (*right*). Points falling on the diagonal legs of the gray triangles have a first occurrence at the corresponding time interval and a last occurrence at the P/T boundary (*top*) or a last occurrence at the corresponding time interval and a first occurrence after the P/T boundary (*bottom*). Sections that span the Permian/Triassic occupy the unshaded region between the two triangles. This figure illustrates the fundamental temporal disjunction that occurs between the Paleozoic and post-Paleozoic sedimentary records in North America.

Phanerozoic trend in either measure. This means that, on average, the durations of packages have not increased or decreased markedly over the course of the Phanerozoic. Extinction rates within shorter intervals, such as the Silurian to Permian, do exhibit temporal trends, indicating that there is fine-scale temporal structure in the expected durations of sedimentary packages.

The combined durations of all sedimentary rock packages are approximately exponentially distributed (ln[number of packages] $= -0.030t + 6.38$; $r^2 = 0.915$, $p < 0.0001$; standard error of decay constant = 0.002), but there are generally more long-duration packages than predicted by a single exponential distribution (fig. 12). Excess long-duration packages could be the result of mixing sedimentary environments with different characteristic half-lives or failing to recognize hiatuses in poorly studied stratigraphic intervals. If 18 packages over 160 m.yr. in duration are excluded (0.58% of the total number of sedimentary packages), then the best-fit exponential decay constant increases to 0.041 ± 0.002 (expected mean duration is 24.4 m.yr.). Despite the uncertainty imposed by long-duration packages, previous estimates of basin longevities are highly consistent with these durations (Woodcock 2004), suggesting that basin fill successions and tectonic subsidence dominate the temporal continuity of the sedimentary record at the approximate temporal resolution of substages (Wilkinson et al. 1991).

Sedimentary Rocks: Accumulation Rates. Because the COSUNA charts provide estimates of thickness for many rock units (only 9% of sedimentary packages have no thickness reported for any of the units), it is possible to crudely estimate long-term accumulation rates. Estimates are only approximate for three reasons. First, the durations of packages are determined on the basis of the ages of stage boundaries. However, packages need not span the entire interval of their first and/or last occurrence, and therefore many packages may be shorter in duration than calculated here (bias in favor of lower sedimentation rate). Second, not every stratigraphic unit within a gap-bound package has a reported thickness, and these omissions are not explicitly addressed here (bias in favor of lower sedimentation rate). Finally, many units are given a maximum and minimum thickness, but only the maximum thickness estimate was used for each package (bias in favor of higher sedimentation rate).

Despite such limitations, the estimated long-term average accumulation rate for all COSUNA sedimentary packages (mean = 35.0 m/m.yr., median = 15.6 m/m.yr.) is very consistent with other long-term accumulation rate estimates (Ronov et al. 1980; Sadler 1981). Thus, it is unlikely that the rates of accumulation reported here are systematically or substantially biased.

Individual estimates for rates of accumulation within individual COSUNA packages vary over three orders of magnitude (fig. 13). There is also considerable short-term variability as well as a significant ($p \ll 0.0001$, Mann-Whitney U-test) Paleozoic to post-Paleozoic increase in average rates of accumulation (Paleozoic mean = 23.7 m/m.yr., median = 12.6 m/m.yr.; post-Paleozoic mean = 46.8 m/m.yr., median = 18.7 m/m.yr.).

Much of the within-interval variance in rates of

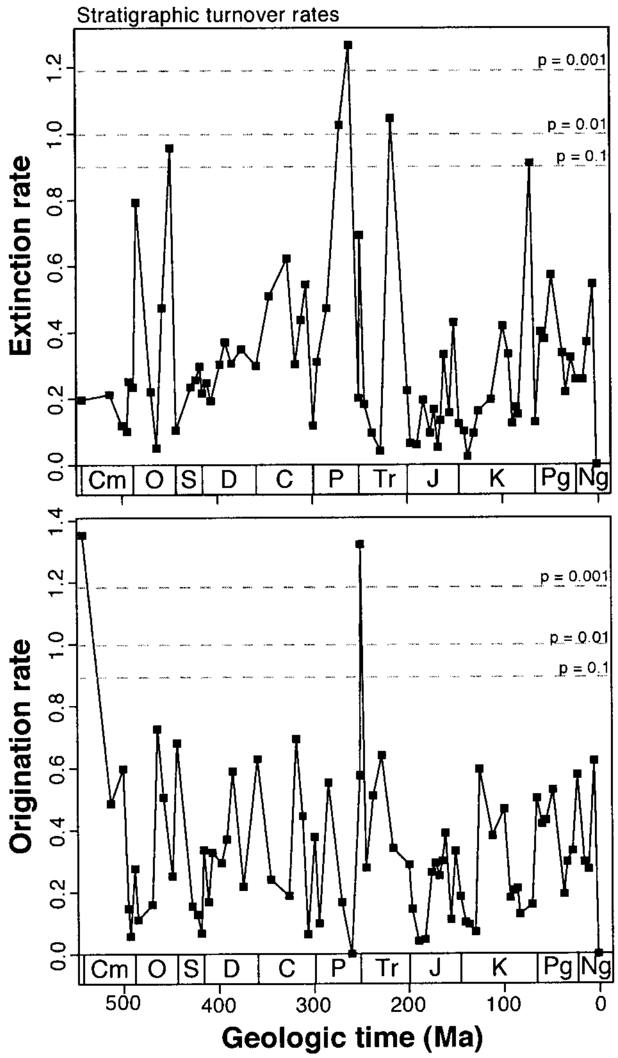

Figure 11. Time series of per-interval rates of stratigraphic extinction (*top*) and stratigraphic origination (*bottom*) for all sedimentary rock packages (data from fig. 5). Rates are calculated using Foote's (2000) survivorship-based rate estimates. Horizontal lines and corresponding decimal values correspond to the probability of obtaining at least one rate as great as or greater than the specific rate in any time interval in a temporal randomization of the observed sedimentary packages. Note that several peaks in stratigraphic extinction are greater than expected by a homogeneous model of package truncation, but only two rates of stratigraphic origination are larger than expected by a homogeneous model of package initiation.

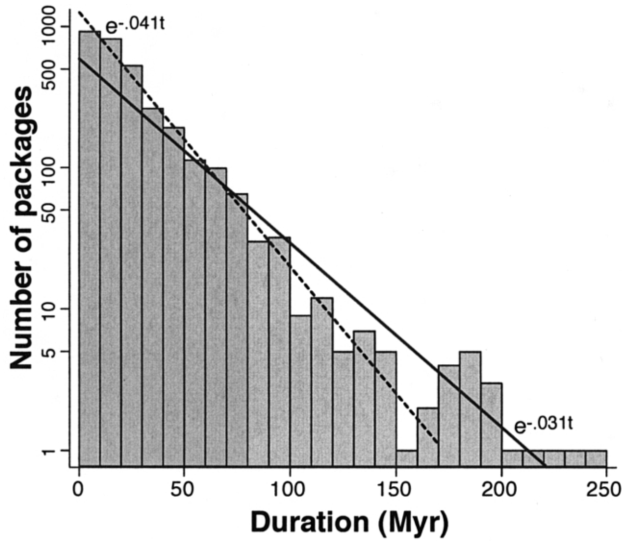

Figure 12. Frequency distribution of the duration of sedimentary packages measured in millions of years and plotted on a logarithmic ordinate. When all packages are included, the best-fit exponential function has a decay constant of −0.031, but there are more long-duration packages than expected. If the few packages >60 m.yr. are excluded, the best-fit exponential function has a decay constant of −0.041.

sedimentation reflects the contributions of tectonic basins with markedly different subsidence rates. For example, high rates of sediment accumulation in the Silurian and Devonian occur in extensional basins that appear to be associated with synorogenic collapse in the northeastern margin of the continent (Tremblay and Pinet 2005). Comparably high rates of Cenozoic sedimentation also occur in the pull-apart basins of southern California, such as the Salton Trough (Dorsey and Martin-Barajas 1999). These basins stand in stark contrast to the slowly thermally subsiding basins of the cratonic interior that are of great importance in the Paleozoic. The combination of these disparate structural basin types is probably responsible for most of the variance in long-term accumulation rates reported here and elsewhere.

The long-term increase in sedimentation rates (particularly after the Devonian) also partly reflects a temporal shift in the average tectonic context of preserved sediment. Slowly subsiding cratonic basins dominate the sedimentary record in the Paleozoic, while the more rapidly subsiding foreland basins in the western United States dominate the Mesozoic record. Pull-apart and other rapidly subsiding fault-bound basins are common in the Cenozoic of the western United States but are nearly

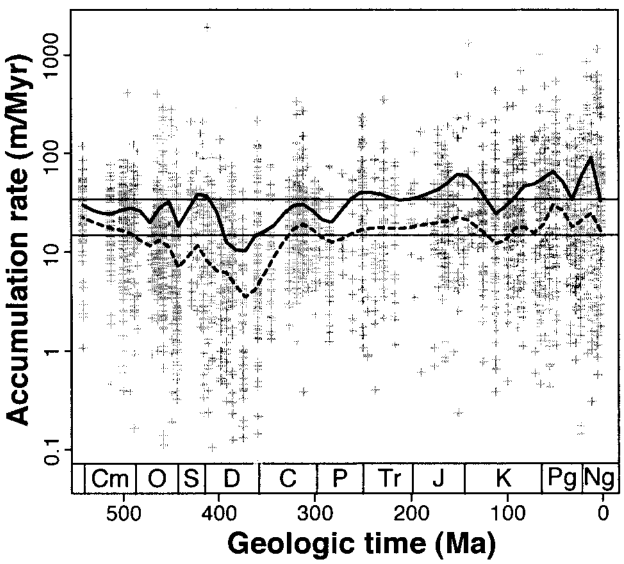

Figure 13. Long-term average sediment accumulation rates calculated for all sedimentary packages and plotted on a logarithmic scale at the maximum age for their interval of first occurrence. Lines are tricubic distance-weighted regressions (LOESS regressions) calculated at stage boundaries using $\alpha = 0.2$. Solid line uses linearly scaled sedimentation rates; dashed line uses natural log-transformed rates. This figure shows both short- and long-term variability in long-term rates of sediment accumulation. Note a Phanerozoic increase in average rates of accumulation.

absent in most of the Phanerozoic (Veizer and Ernst 1996). Carbonate sediments also have lower average rates of accumulation (mean = 18 m/m.yr., median = 11 m/m.yr.) than terrigenous clastic sediments (mean = 38 m/m.yr., median = 14 m/m.yr.), and there is a compositional shift from carbonates to clastics during the course of the Phanerozoic (fig. 6) that is also possibly related to the shifting tectonic context of preserved sediment (Wilkinson and Walker 1989; Walker et al. 2002).

Sadler (1981) pointed out that apparent sediment accumulation rates are inversely correlated with the duration over which the rate is measured, and he attributed this, in part, to the increasing prevalence of gaps in long geologic columns and the generally episodic nature of sediment accumulation. There is no similar inverse relationship between accumulation rate and the duration of sedimentary packages in the COSUNA data (fig. 14), but this is not surprising for two reasons. First, because gap-bound packages of sediment are being compiled here, all gaps that are evident at the substage level of temporal resolution are already excluded from the ranges of packages. Thus, long gap-bound packages do not incorporate more long gaps than their shorter counterparts. Second, package durations in this study span only approximately three orders of magnitude, and the rate-duration correlation is apparent only when very short durations are also included (Sadler 1981; Schlager 1999). In fact, the rate-duration results reported here are closely comparable to those reported by Sadler (1981) over the same scales of rate and duration (Sadler's rate mode IV). A more detailed analysis of Phanerozoic rates of sedimentation in the COSUNA data and the controls on the rate-duration relationships at different temporal scales will be presented in future work, but it seems likely that at million-year timescales, broadly similar rates of tectonic subsidence control rates of sedimentation (Wilkinson et al. 1991; Sadler 1993).

Igneous Rocks. Compiling gap-bound packages of sedimentary rock is a logical extension of the principles of sequence stratigraphy and is therefore grounded in existing theoretical principles for basin fill successions, but gap-bound igneous packages do not fit easily into any current theoretical framework for quantifying igneous processes. Nevertheless, like sedimentary rocks, igneous rocks are emplaced or extruded continuously at any given scale

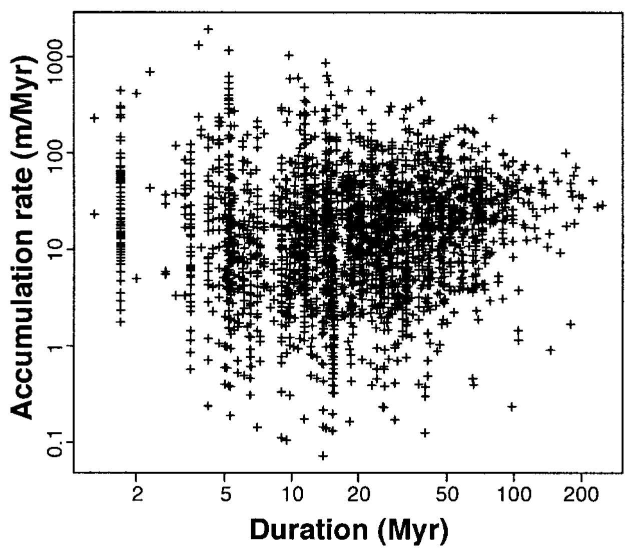

Figure 14. Log-log plot of long-term average sediment accumulation rates for all sedimentary packages plotted against their durations. The lack of correlation between rate and duration in these data suggests that tectonic subsidence is the dominant process controlling rates of sedimentation on million-year scales.

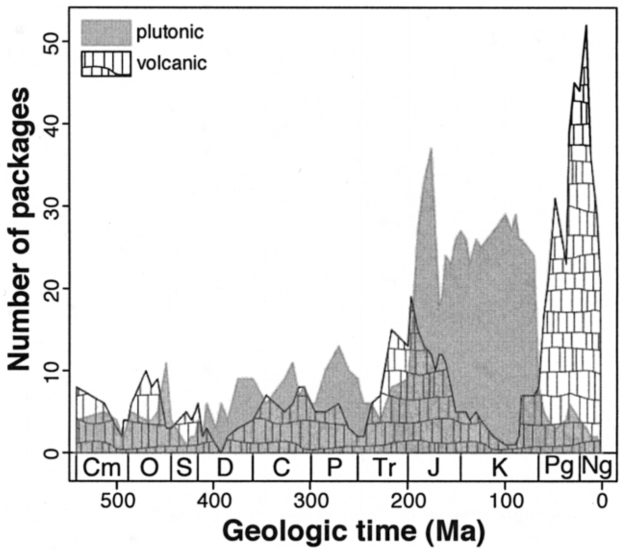

Figure 15. Time series of the total number of volcanic packages and the total number of plutonic packages plotted separately. Data are plotted at age for each interval base. This figure shows the prominent plateau of plutonic rock that occurs in the late Mesozoic and the prominent increase in the quantity of volcanic rock in the Cenozoic.

of temporal resolution and therefore have the same temporal structure as sedimentary rock bodies.

Phanerozoic time series for the total number of preserved packages of intrusive and extrusive igneous rocks are shown in figure 15. The volcanic component includes both submarine volcanics (which are dominant in the Paleozoic, particularly in accreted island arcs) and terrestrial flows (which are dominant in the Cenozoic). Like the record of terrestrial sediment (fig. 8), there is a large Cenozoic increase in the number of preserved volcanic packages. This reflects the onset of extensive and geologically young volcanism in the western half of the United States, mainly in response to crustal extension in the Basin and Range Province and arc volcanism associated with the subduction of the Farallon Plate, which is still ongoing in the Pacific Northwest.

The most striking temporal pattern in the number of plutonic packages is a rather prominent Jurassic and Cretaceous plateau. This reflects the extensive emplacement of large plutons in the western United States, primarily in response to the extensive arc magmatism associated with the subduction of the Farallon Plate during this time. Interestingly, the number of volcanic packages decreases just as the number of plutonic packages increases in the Jurassic and increases just as the number of plutonic packages decreases in the Cenozoic. The net result is a volcanic-plutonic-volcanic alternation superimposed on an interval of a nearly constant total number of igneous packages (fig. 16). This interval of stability in the total number of igneous packages closely coincides with the Cretaceous quiet interval of normal magnetic polarity (Gradstein et al. 2004), but why approximately constant igneous rock quantity should be associated with a long interval of normal polarity is not entirely clear, and the coincidence may be just that.

Discussion

Characterizing the small- (fig. 2) and large-scale (figs. 5–16) temporal and spatial structure of the geologic record is important because many disparate geologic processes control the formation and destruction of rock bodies and because these processes may exert a strong influence on many other interacting phenomena, such as biological evolution (Newell 1952, 1967; Valentine and Moores 1970; Johnson 1974; Sepkoski 1976; Peters and Foote 2001, 2002; Smith 2001; Smith et al. 2001; Foote 2003; Peters 2005), carbon cycling (Worsley et al. 1985, 1986), and climate (e.g., Herrmann et

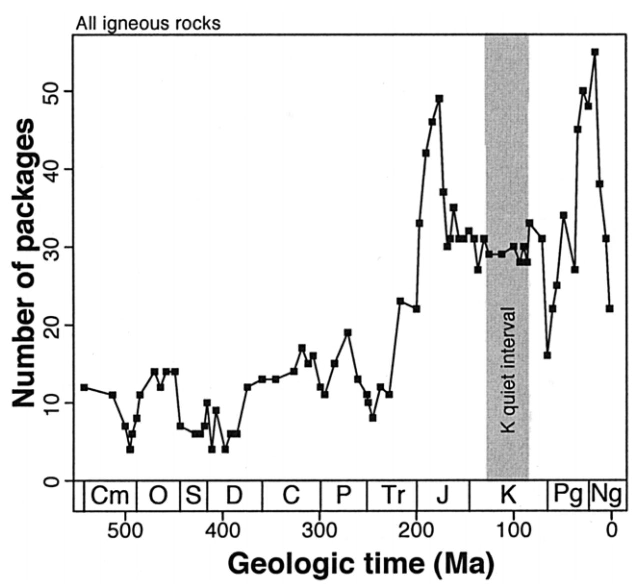

Figure 16. Time series as in figure 15 but plotted as the sum of both extrusive and intrusive igneous rocks. Shaded area corresponds to the Cretaceous quiet interval of normal magnetic polarity (plotted here as Barremian to Santonian). Data are plotted at age of each interval base.

al. 2004). Much of the previous work that quantified the geologic record used geologic maps to estimate preserved rock volumes and general lithologies and from these rock cycling rates (Gregor 1968, 1985; Ronov 1978; Berry and Wilkinson 1994; Walker et al. 2002). Quantifying the geologic record on the basis of gap-bound packages of rock capitalizes on a fundamental temporal and spatial structure in the geologic record and stands to contribute greatly to our understanding of the processes that have controlled the formation and destruction of rock bodies over geological time.

The realization that the geological record has a fundamental temporal and spatial structure that can be quantified opens up a wide range of empirical possibilities. By definition, rock packages are geographically precisely located and therefore preserve the highest possible spatial resolution. Temporal resolution is limited only by one's ability to correlate and to precisely identify the ages of unconformities and the durations of hiatuses. Gap-bound rock packages also record a series of measurable units, each of which can be described by numerous physical, chemical, environmental, and/or biologic parameters. In other words, gap-bound packages of rock are well-defined, fundamental units of sampling in the geological record that have a finite temporal range, a precise geographic location, and a suite of defining characters that are related to the composition of the rock bodies and the geologic and environmental processes responsible for their formation and destruction.

At the approximate temporal resolution of stages in the Phanerozoic, the sedimentary rock record reveals striking long- and short-term variability in composition, temporal continuity, and quantity. Much of this variability appears to be the result of the net northward migration of Laurentia during the Phanerozoic (Allison and Briggs 1993; Veizer and Ernst 1996), combined with large-scale tectonic uplift/subsidence (Ziegler and Rowley 1998) and/or concomitant long-lived eustatic changes in sea level. In the COSUNA data, long-term patterns of sedimentary rock quantity (fig. 5) closely resemble the so-called "m curve" of Phanerozoic sea level (Vail et al. 1977; Hallam 1984, 1989; Haq et al. 1987; Miller et al. 2005) and the corresponding tectonic cycles of continental aggregation and breakup (Worsley et al. 1984, 1986; Heller and Angevine 1985; Nance et al. 1986; Veizer and Ernst 1996). The Cenozoic divergence between sea level and total rock quantity reflects the increasing prevalence of nonmarine sediments in the younger part of the geologic record (fig. 8) and the contribution of abundant, geologically young sediments that are unlikely to persist into the long-term geologic record.

Shorter-term variability in the sedimentary record, particularly in the pre-Cenozoic, also appears to be driven primarily by processes related to the expansion and contraction of epicontinental seas. For example, the Great American Carbonate Bank (Ginsburg 1982) that dominates the sedimentary record of the Late Cambrian and Early Ordovician (fig. 6) underwent widespread truncation in the Arenigian (fig. 11) that resulted in a substantial decline in the amount of preserved sediment in the following stage (fig. 5). The Arenigian break in the sedimentary record of North America likely reflects a relatively modest decrease in sea level that was strongly accentuated by the widespread draining of extensive and shallowly flooded carbonate platforms. Regions lacking extensive carbonate banks probably do not record a similarly large pulse of stratigraphic extinction during the Arenigian.

The second major pulse of stratigraphic extinction in the Phanerozoic occurs in the Ashgillian and is coincident with widespread Gondwanan glaciation and an apparent major mass extinction (Berry and Boucot 1973; Raup and Sepkoski 1982). This suggests that a glacioeustatic drop in sea level caused the termination of sediment accumulation and the truncation of sedimentary rock bodies. Unlike the Arenigian peak in stratigraphic extinction, however, a large drop in the number of preserved sedimentary packages does not follow the Ashgillian because a small pulse of stratigraphic origination immediately follows the pulse of stratigraphic extinction. The Ordovician-Silurian boundary therefore records a turnover of sedimentary packages, but standing rock quantity remains relatively constant in the Llandovery. Similar patterns have been documented for marine animal genera at the Ordovician/Silurian (Krug and Patzkowsky 2004; Ausich and Peters 2005). However, because most Llandovery packages have first occurrences in the upper portion of this very long stage, at finer scales of temporal resolution, there may be a much more pronounced drop in stratigraphic diversity after the Ashgillian.

The largest temporal discontinuity in the sedimentary record of North America occurs at the Permian/Triassic (figs. 9–11), but the peak in stratigraphic extinction that occurs at the boundary is part of a Permian-long retreat of Laurentian epicontinental seas. It is important to note that the end-Permian has long been associated with regression (e.g., Newell 1952, 1967), but the following Lower Triassic interval also preserves a large pulse of stratigraphic origination (fig. 11). Well-preserved regional histories of relative sea level in China also record transgression at the Permian/Triassic (Wignall and Hallam 1993; Wu et al. 1993), and these local, Early Triassic observations have caused some to question the pervasiveness of the low stand in sea level at the end-Permian (e.g., Hallam and Wignall 1999). The temporal continuity of the sedimentary record in North America is consistent with a Permian-long sea level fall culminating in a Phanerozoic low stand that is followed immediately by sea level rise and the re-expansion of (mostly restricted) marine environments. Regional Permian/Triassic boundary sections that preserve an uninterrupted sedimentary history are therefore expected to show transgression at or very near the boundary interval, but this does not mean that the latest Permian did not witness dropping sea level and high rates of sedimentary rock package truncation.

In the Late Mesozoic and Cenozoic records, the increasing prevalence of geologically shorter-lived tectonic basins and the disappearance of extensive continental seaways strongly influenced the character of sediment accumulation and have contributed to a dramatic increase in the amount of preserved rock as well as to an overall increase in rates of sediment accumulation. Because a large proportion of the preserved Cenozoic sedimentary record is presently exposed on the continents and is geologically very young, it is likely that these sediments will be rapidly recycled and ultimately redeposited in sedimentary basins with much longer geologic half-lives.

As an example of sediments that are likely to have rather short geologic half-lives, the increase in the number of conglomerate packages during the Phanerozoic (figs. 7, 8) is unlikely to be the result of a strong temporal increase in the production of conglomeratic sediments but instead may simply reflect the increasing prevalence of abundant and geologically ephemeral sediments in the young portions of the record. On shorter timescales, the transient nature of recent sediment accumulation is evidenced by the tremendous volumes of sediment that are currently being deposited on global river floodplains in response to human-induced agricultural runoff (Costa 1975; Bettis and Mandel 2002). This voluminous sedimentary record, although very large in comparison to the world's total sediment budget (Wilkinson 2005), is exceedingly unlikely to be preserved in the long-term geological record because regions of flood-plain sedimentation remain above base level and are therefore found in regions of long-term net denudation. The young (i.e., Late Cretaceous to Recent) geologic record contains many similar, if less dramatic, examples and is in many respects not directly comparable to the older geologic record. The general qualitative effects of variability in the longevity of depositional systems has been known for some time (Gilluly 1969; Gilluly et al. 1970), but the data to test for and calibrate such effects will be realized only with the expansion of this approach to include more finely resolved paleoenvironmental and tectonic data.

Although many previously unknown aspects of the geologic record have been documented in this preliminary analysis (e.g., turnover of sedimentary environments, stage-level variation in lithofacies and sedimentation rates, temporal continuity of the sedimentary record, and probabilities of rock package origination and extinction), the real strength of the new methodological approach outlined here will be fully realized only when primary field descriptions of actual measured geologic transects are compiled and applied to specific geological questions at the appropriate temporal resolutions for the problems being addressed. For example, figure 2 shows a hypothetical two-dimensional projection of a rather simple sequence architecture. Quantifying the turnover of sedimentary environments and the architecture of real depositional basins on the basis of well logs and/or measured stratigraphic transects will help to constrain the timing, magnitudes, and extents of tectonic processes, environmental changes, and the causes of macroevolutionary patterns in the fossil record on the finest possible temporal and spatial scales.

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